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**Final Report
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Earth Radiation Measurement Science

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Introduction

This document is the final report for NASA Grant NAG1-1959, "Earth Radiation Measurement Science." The purpose of this grant was to perform research in this area for the needs of the Clouds and Earth Radiant Energy System (CERES) project and for the Earth Radiation Budget Experiment (ERBE), which are being conducted by the Radiation and Aerosols Branch of the Atmospheric Sciences Division of Langley Research Center. Earth Radiation Measurement Science investigates the processes by which measurements are converted into data products. As such, it is not the purview of the instrument engineer, but begins with the measurements. It is not the interest of the atmospheric scientist, who is not familiar with the measurements or the implications of the data processing. Most of the work of RAAB is in this area. Under this grant, research was to be conducted for 5 tasks. This grant was for one person, half time for 3 years. In order to accomplish these tasks, the principle investigator collaborated extensively with RAAB scientists, both in-house and contractor.

During the period of this grant 2 other opportunities arose. The UK in collaboration with Belgium and Italy built a Geosynchronous Earth Radiation Budget (GERB) instrument, to fly on the MeteoSat Second Generation spacecraft in 2001. I became a member of the GERB International Science Team. Also, the Triana project was begun to place a spacecraft at the first Lagrangean point, a million miles from Earth toward the Sun. I was invited to participate on the science team for this project.

A synopsis of research performed for each of the tasks is given here. A list of papers produced under this grant follows. In the synopsis of research, the numbers in parentheses refer to the numbers in the listing of papers documenting this work.

Task 1: Point Response Function Measurements

The measurements of the point response function for the CERES Proto-Flight Model (PFM), Flight Model-1, -2, -3 and -4 were analyzed and reported. The steps to develop a point response function were also reported (2, 23).

Calibration testing of the CERES instrument showed the presence of a spurious transient, which could compromise the accuracy of the data if not properly treated. The PI designed a numerical filter to eliminate this effect. Ground calibration data were analyzed to characterize the transient for PFM and FM-1, -2, -3 and -4. The numerical filter was made operational in the data processing software and the effects of the transient have been eliminated from the instrument data stream (32).

The method for validating pixel location was developed and the pixel location was validated by coastline studies for PFM (3).

Task 2: Temporal Sampling of Outgoing Longwave Radiation

Intercomparison studies of monthly-mean maps produced from the ERBS wide field-of-view radiometers had shown that there were errors in the maps due to temporal sampling problems when only the ERBS is available. Algorithms were developed for both outgoing longwave radiation and reflected solar radiation (4, 5, 14) and made operational in the ERBE data processing software and applied to 14 years of the ERBS data set (16). The results have been studied and reported (26).

Task 3: Spatial Averaging of Radiation Budget Data

This task was made moot by the decision to use biaxial scanning data to compute spatial averages and no action was taken here. This was good because it made the required time available for the GERB and Triana opportunities.

Task 4: CERES Data Validation and Applications

A number of papers were written to document and inform the scientific community of the status of the CERES data, its validation and some applications (1, 6, 9, 10, 11, 12, 13, 21, 31, 33, 34, 35).

Task 5: ScaRaB Data Validation and Application

The ScaRaB 2 was placed into orbit aboard a Russian Meteor spacecraft. We made Intercomparisons between ScaRaB-2 and the ERBS WFOV radiometers (18). The ERBS compared as well with ScaRaB-2 as it did with the ERBS scanner.

Additional tasks:

In support of the GERB instrument, provided consultation for application of data to scientific investigations (Attachment A) and validation of GERB data products (30)

In support of Triana, contributed to Science Plan and studied interpretation of measurements of irradiance from full disc of Earth from Triana. It was demonstrated analytically that the measurement of outgoing longwave radiation has a bias of 6 to 10 W-m⁻², which is easily computed and taken into account (20). Another paper formulates a phase function which incorporates the anisotropy of the reflected solar radiation in order to interpret the reflected solar radiation measurements (24).

Studies were made of the Surface Radiation Budget (SRB) data set which has been generated at LaRC. It was demonstrated that the climate classification of a region can be determined from the surface radiation data using very simple criteria, thus showing the close relation between SRB and climate at the regional scale (7, 22, 28). Studies using the ERBE (19, 25, 29) data set found an interannual variation in reflected shortwave radiation in the Indian and west Pacific Oceans. There may be implications here for the Indian and Southwest Asian monsoons.

Other studies of Earth radiation measurements (8) and related topics were conducted relating to biases induced by the orbit (15), anisotropy of upwelling radiation (17) and relation of spatial and temporal sampling and requirements (27).

Copies of the following papers are attached, as they will not appear in print for some time:

Smith, G. L. and M. G. Mlynczak, 2000: "CERES and GERB validation," presented at the First MSG RAO Workshop, , 17-19 May, Bologna, Italy (paper 30)

Smith, G. L., T. D. Bess, N. Manalo-Smith, V. Ramanathan, R. B. Lee III and B. R. Barkstrom "Results from the CERES 8-12 micron window channel," presented 33-rd COSPAR Scientific Assembly, Symposium on Space Studies of the Earth's Surface, Meteorology and Climate, 16-23 July, Warsaw, Poland (paper 31).

Papers written during the Period of Performance

1. Smith, G. L., R. B. Lee III, B. R. Barkstrom, B. A. Wielicki, K. J. Priestley, S. Thomas, J. Paden, R. S. Wilson, D. K. Pandey and K. L. Thornhill, 1998: Overview of CERES Sensors and In-flight Performance, *Optical Sci., Eng. & Instrum., Proc.*, SPIE, v. 3439, 19-24 July, 1998.
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24. Smith, G. L., 1999: Simulation of full Earth disc measurement at L-1 of reflected solar radiation, *Proc. Sensors, Systems and Next Generation Satellites III*, 117-125, Europto, 20-23 September, Florence, Italy.
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CERES AND GERB VALIDATION STUDIES

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1. INTRODUCTION

The Geosynchronous Earth Radiation Budget GERB instrument aboard the MeteoSat Second Generation Satellite will provide measurements every 15 minutes of the MeteoSat region of the Earth for Outgoing Longwave Radiation OLR and for Reflected Solar Radiation RSR. There are 2 Clouds and Earth Radiant Energy System CERES instruments on the TERRA spacecraft in Sun-synchronous orbit whose results can be compared to those of GERB. The AQUA spacecraft is scheduled to be placed in orbit and in early 2001 should be providing data from 2 more CERES instruments. A major part of CERES validation is comparison of results from the various CERES instruments and also with the Earth Radiation Budget Experiment Wide field-of-view radiometers aboard the Earth Radiation Budget Satellite. The latter comparisons provide a link with the ERBE data set, to give a continuity of Earth radiation measurements. Comparisons will place GERB on the same Broadband Radiometric Scale of satellite measurements as ERBE and CERES. Figure 1 shows the Earth radiation budget record over the years.

There are several steps which produce a sequence of data products, each of which needs to be validated. From the instrument counts and the calibrations the radiances are computed. Next, the radiances are used to compute the radiant fluxes, which involves accounting for the anisotropy of the radiation leaving the "top of the atmosphere," by use of bidirectional reflectance distribution functions BRDFs. The fluxes are computed then for grid regions, which are 1 degree in latitude and longitude. Finally, daily averages are computed. The comparison of products between GERB and CERES for each of these steps will now be described. Typically, the comparison of 2 data sets improves the products from both. For comparison studies, the measurements should be taken as close together in time as possible. For GERB, this is no problem. The CERES measurements will always be taken within 7.5 minutes of a GERB measurement.

2. RADIANCES

The instrument measures total and shortwave radiances at the detector. These radiances differ from the radiances entering the instruments due to the spectral response of the instrument, so we denote them as filtered radiances. From the filtered radiances, the longwave and shortwave The unfiltered radiances which entered the instrument are computed, which we denote as unfiltered radiances. GERB uses an array of 256 detectors, each of which views a narrow latitude band. The unfiltered radiances from each of these detectors should be compared to unfiltered radiances from the CERES instruments. Because of the anisotropy of reflected solar radiation, the ray which is observed by GERB should be close in angle to the ray observed by CERES. CERES instruments operate primarily in one of 3 scan modes, each of which impose constraints on the observation of a ray by both the GERB and by CERES. The sampling of radiances measured by both instruments is now considered for each CERES scan mode.

For mapping the radiative flux from the Earth, a CERES instrument scans cross-track, as shown in Fig. 2. The rays which are viewed by CERES lie in a plane which is normal to the TERRA orbit plane and moves with the spacecraft as it goes around its orbit. The only ray which is observed by GERB and CERES is the ray along the intersection of the orbit planes of the MSG and the TERRA spacecraft. It is the nadir ray from each spacecraft as they cross, which is at 10:30 local solar time and 10:30 GMT. There is a ray on the Sun-lit side of Earth (10:30 AM) and one on the night side (10:30 PM, or 2230

hours). Also, the radiance will be viewed only if TERRA crosses the intersection near the same time as MSG. As a consequence, only measurements near the Equator can be compared with CERES in the cross-track mode, so that only a few detectors can be compared.

The other CERES instrument aboard TERRA is primarily for making radiance measurements for the development of improved BRDFs. This instrument is periodically oriented so as to scan in the orbit plane, i.e. alongtrack, as Fig. 3 shows. For this case, as MSG passes through the TERRA orbit plane, the line from MSG to TERRA corresponds to a ray which is observed by both GERB and CERES. This ray moves with the TERRA spacecraft. Each time the MSG passes through the TERRA orbit plane, TERRA will be in a different location. Over a long period of time, in this CERES scan mode each of the GERB detectors will observe radiances jointly with CERES.

For its third scan mode, the CERES instrument which is devoted to gathering data for BRDF developments scans in azimuth as well as in elevation. Figure 4 shows the Rotating Azimuth Plane Scan mode. For this case, there are no constraints on the geometry as for the first 2 scan modes and a measurement is possible for any line from the MSG to the TERRA to Earth. Because measurements are taken at a constant rate, and the scan rates in azimuth and elevation angle are constants, the number of measurements is greatest near the orbit plane of TERRA. Over a period of time in this CERES scan mode each of the GERB detectors will observe radiances jointly with CERES.

In practice, these conditions must be relaxed, e.g. if the rays from a site to the 2 spacecraft are within 5° they will be used.

3. PIXEL FLUXES

The flux is derived from the radiances by use of BRDFs to account for the anisotropy of the OLR and RSR. Except for the special conditions described in the previous section, GERB and CERES will view any site from different angles. Errors of the BRDFs will result in different fluxes being computed for the 2 instruments. These checks will validate the fluxes produced by both instruments and also the BRDFs.

4. REGIONAL MEAN FLUXES

The GERB pixel is 49 km at the sub-satellite point, and is 125 km at the corners of the METEOSAT sector, where the view zenith angle is 68° (J. Delderfield and Martin Caldwell, MSD-RAL-GE-TN-0007). As a consequence, when regional averages are formed, there are errors associated with their computation from the relatively large pixels, especially at the corners of the sector. The CERES has a pixel size which is 20 km near nadir and TERRA orbit passes can be selected such that a given GERB region, e.g. a sector corner, is observed by CERES near nadir. In this manner the spatial averaging errors can be quantified experimentally. There is a problem that the regional mean flux error includes not only the spatial averaging error, but also the BRDF errors, for both instruments. The BRDF errors can be minimized by considering the OLR case, for which the BRDF (limb-darkening functions) are near 1 and errors are small compared to the RFR case.

5. TIME INTERPOLATED/AVERAGED FLUXES

GERB observes every 1° region within the METEOSAT sector of the Earth every 15 minutes. At this spatial scale, the temporal sampling is sufficient that temporal sampling errors are practically zero. One of the major sources of error for the CERES daily mean and monthly mean data products is time-sampling error. In order to form these means, it is necessary to interpolate in time between the measurements. There are 3 effects to be taken into account for CERES. First, there are variations from day to day, or synoptic variations. Next, there are diurnal variations of the scene. Finally, the albedo increases as solar zenith angle increases. The latter effect is accounted for by use of a directional model, which describes the variation of albedo with solar zenith angle. GERB data will provide information for validating the CERES time interpolated and averaged data products.

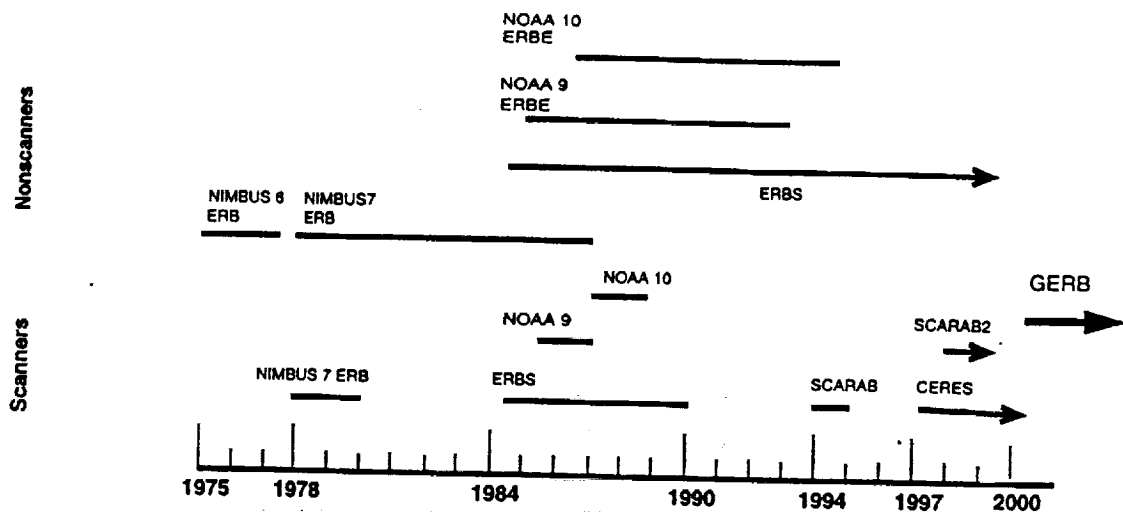


Figure 1. Earth Radiation Budget data sets.

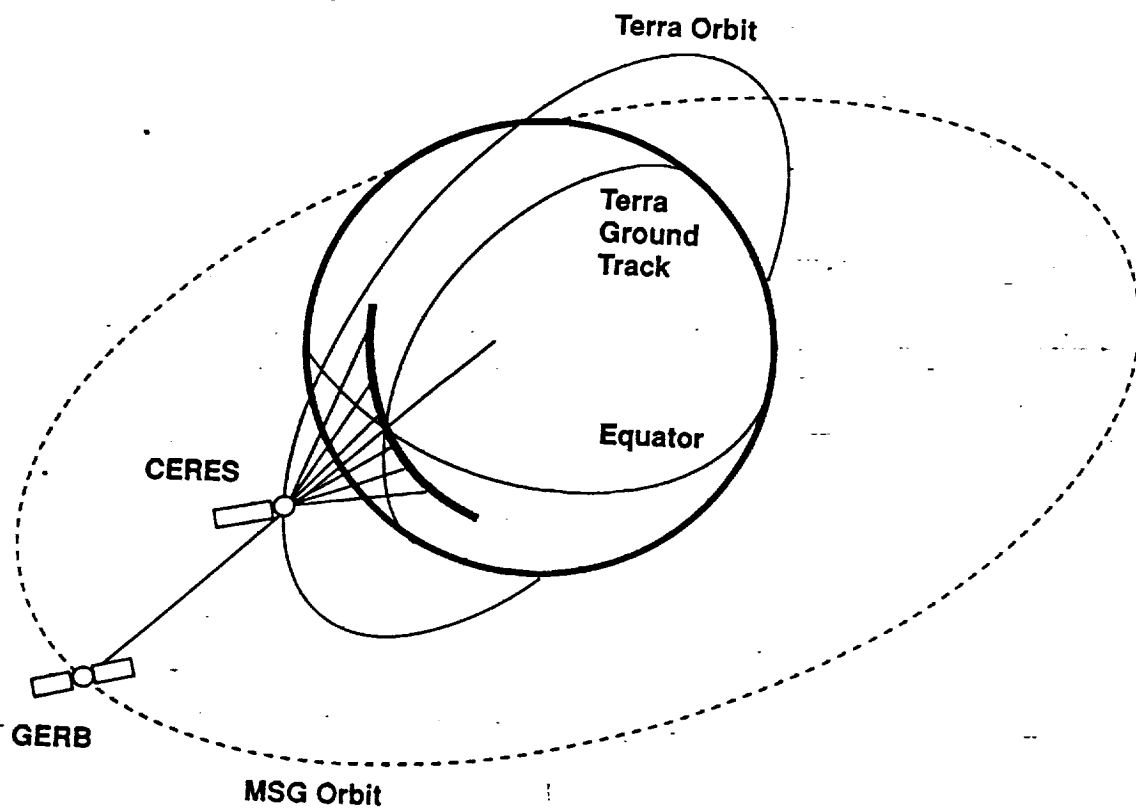


Figure 2. CERES and GERB simultaneous radiance measurements for CERES scanning cross-track.

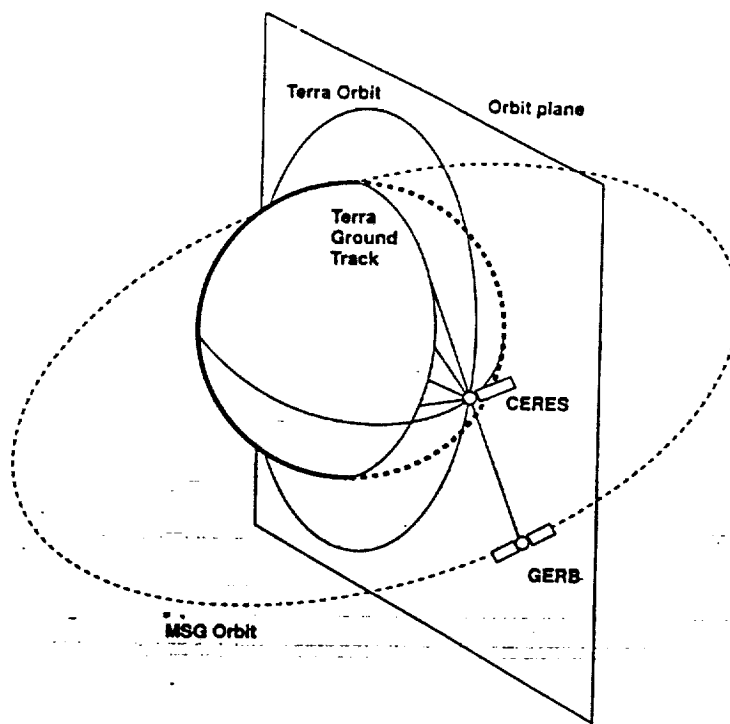


Figure 3. CERES and GERB simultaneous radiance measurements for CERES scanning along-track.

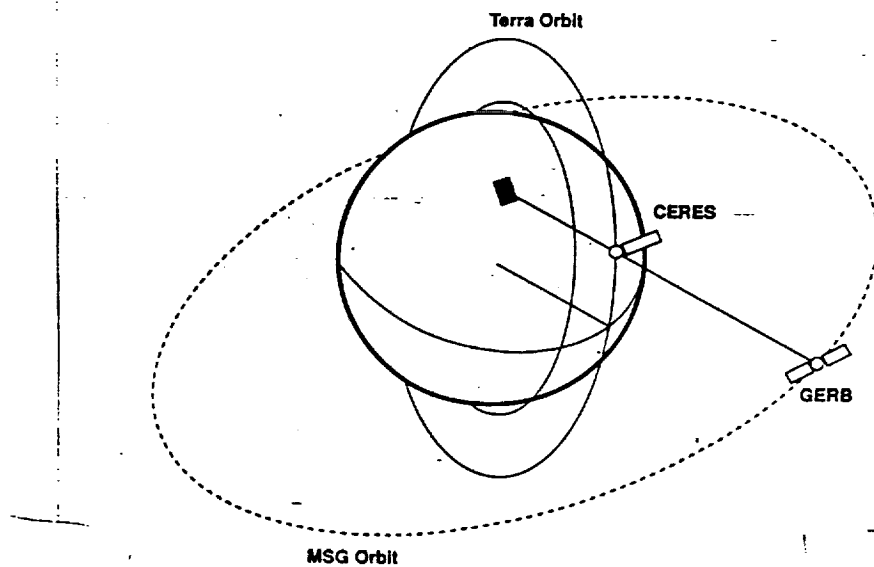


Figure 4. CERES and GERB simultaneous radiance measurements for CERES scanning biaxially.

RESULTS FROM THE CERES 8-12 MICRON WINDOW CHANNEL

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ABSTRACT

The CERES (Clouds and Earth Radiant Energy System) scanning radiometer has 3 channels: a shortwave channel for measuring solar radiation reflected from the Earth, a total channel, which combined with the shortwave channel gives the outgoing longwave radiation, and a channel for measuring radiances in the 8 to 12 μ window of the atmosphere. The CERES instrument aboard the Tropical Rainfall Measurement Mission (TRMM) spacecraft provided 8 months of data. This paper discusses the 8-12 μ channel of the CERES/TRMM data. In order to compute fluxes from radiances measurements, limb-darkening functions are required. The limb-darkening functions are computed from CERES measurements. These functions are then used to compute fluxes from the measured radiances. Finally, maps are examined to show the features of radiation in the window channel.

INTRODUCTION

The Clouds and Earth Radiant Energy System (CERES) instrument is a scanning radiometer which was designed to measure the components of the Earth's radiation budget. The program objectives are described by Barkstrom (1990) and Wielicki et al. (1996). The CERES scanning radiometer has 3 channels: a shortwave channel for measuring solar radiation reflected from the Earth, a total channel, which combined with the shortwave channel gives the outgoing longwave radiation (OLR), and a channel for measuring radiances in the 8 to 12 micron window of the atmosphere. The 8 to 12 μ window is heavily affected by water vapor, which is a greenhouse gas and varies strongly with location and time. Measurements by this channel will thus permit an understanding of the variability of water vapor and its feedback effects in the climate system (e.g. Inamdar and Ramanathan, 1994). The combination of the window channel with the simultaneous broadband measurements of CERES will provide an especially important data set. The CERES Proto-Flight Model, aboard the Tropical Rainfall Measurement Mission (TRMM), provided data from January through August 1998 to cover the Earth from 40° S to 40° N. Flight Model 1 and 2 (FM1 and -2) CERES instruments aboard the Terra spacecraft have been operating since March 2000. Another pair of CERES radiometers are scheduled to fly aboard the Aqua (Earth Observation System Afternoon platform). CERES/TRMM pixel level data are now archived and available for use by researchers. Computation of window fluxes from window radiance measurements requires limb-darkening functions. This paper presents limb-darkening functions which were computed from CERES measurements made as the instrument scanned alongtrack. These functions are then used to compute fluxes from the measured radiances. Maps are examined to show the features of radiation in the window channel and to compare with the broadband OLR map.

INSTRUMENT

Each of the 3 channels of CERES has a thermistor bolometer detector and a Cassegrain-type reflecting telescope to gather radiation, as shown in figure 1. The window channel has a 2-piece interference filter to provide the 8-12 μ spectral response of the channel. One part of the filter is located in front of the primary and secondary mirrors, the other part is located behind the primary mirror. The first part of the filter blocks radiation not in the window channel. Because it absorbs radiation not in the 8-12 μ window, the filter heats up and emits spurious longwave radiation to the detector. The second part of the filter absorbs the portion not in the 8-12 μ range. The thermal inertia of the 2 parts of the filter permits most of the effects of the spurious radiation from the filter to be eliminated by a linear interpolation between space looks. Figure 2 shows the spectral response of each of the 3 CERES channels.

The window channel was calibrated in vacuum by use of a blackbody, which tied the window channel calibration to the International Temperature Scale of 1990 (ITS-90). Lee et al. (1996) describe the techniques for ground calibration of the CERES instruments. The instrument includes a Internal Calibration Module, which has a blackbody for on-orbit calibration of the window channel. Smith et al. (1998) describe the results of on-orbit calibration of the TRMM instrument and Lee et al. (2000) describe the on-orbit calibration of the FM1 and -2 instruments. They demonstrated that the window channel maintained its ties to the ITS-90 with an accuracy of 0.3 $\text{Wm}^{-2} \text{sr}^{-1}$.

LIMB-DARKENING FUNCTIONS

In order to compute flux M from the outgoing radiance L , a limb-darkening function R is used which accounts for the variation of radiance with the zenith angle θ of the exiting ray:

$$M = \frac{\pi L}{R(\theta)} \quad (1)$$

The CERES/TRMM instrument was operated for 9 days to scan alongtrack, which provided measurements from which the limb-darkening function LDF can be computed as was done with Earth Radiation Budget Experiment (ERBE) data (Smith et al., 1988; Smith et al., 1994). The same scene types were used as for ERBE (Suttles et al., 1988) and were computed for each 18° latitude zone from 36°S to 36°N for day and night. Figure 3 shows the LDF for clear sky over ocean and for land in the zone 18°S to 36°S for the 8-12 μ radiances and also for broadband outgoing longwave radiances. Figure 4 shows similar results for partly cloudy sky over ocean and land in the zone from the Equator to 18°N. The LDF for the 8-12 μ window are very similar to those for the broadband case. The LDF can be approximated very well by use of a 2-parameter expression:

$$R(\theta) = \frac{1 + p\mu(1 - e^{-\tau/\mu}) - p\tau}{1 + p\left[\frac{2}{3} - 2E_4(\tau) - \tau\right]} \quad (2)$$

where $\mu = \cos \theta$, E_4 is the fourth-order exponential integral. The p and τ are not considered to be physical parameters but are fit to the data for each scene type. Root-mean-square error for the curve fits are less than 0.005 for view zenith angle θ less than 70°. The p and τ for the 12 scene types for these 4 latitude bands for day and night. Table 1 lists p and τ for the day models. With these parameters and equation 2, an LDF can be computed which does not have the random errors, primarily due to sampling, which are present in the direct computation of LDF from the data.

MAPS

Pixel data for CERES are listed on the ES-8 file, which includes the shortwave, broadband longwave and window radiances for each channel and the broadband OLR, pixel location, the scene type (under the ERBE classification) view zenith angle, solar zenith and azimuth angles, the fluxes for OLR and reflected solar radiation and sundry other information. With the scene type and view zenith angle listed for each pixel, the appropriate limb-darkening function can be selected and used to compute window channel flux for the pixel. Pixel flux values were gridded using a grid which is 1° in both latitude and longitude. Minnis et al. (1984) demonstrated that window channel radiation has a diurnal cycle which can be described by a half-sine fit. Nevertheless, within each grid box a simple average was computed for the day for expediency. The quantity listed for the window on ES-8 is the specific radiance, $\text{Wm}^{-2}\text{sr}^{-1}\mu^{-1}$. In order to compute radiance, an effective window width of 3.7μ is used. Figure 5 is a map of the 8-12 μ flux thus computed over the latitude range from 40°S to 40°N for 1 January 1998.

Figure 6 is a map of broadband OLR, also for 1 January 1998, similarly computed for comparison. The 2 maps show very similar features but the broadband OLR flux is approximately 3 times the window flux. Although both fluxes were gridded and time-averaged in the same manner, artifacts appear in the broadband map which do not appear in the window flux map. There are other differences which are more subtle and which should be more interesting scientifically.

CONCLUDING REMARKS

The pixel level data for the 8-12 μ window channel as well as the longwave and reflected solar radiation are available to researchers for the CERES/TRMM data as ES-8 files at the Langley Distribute Active Archive Centre and can be accessed via the web at URL

http://eosweb.larc.nasa.gov/project/ceres/table_ceres.html

CERES BAFFLE, TELESCOPE AND DETECTION MODULES

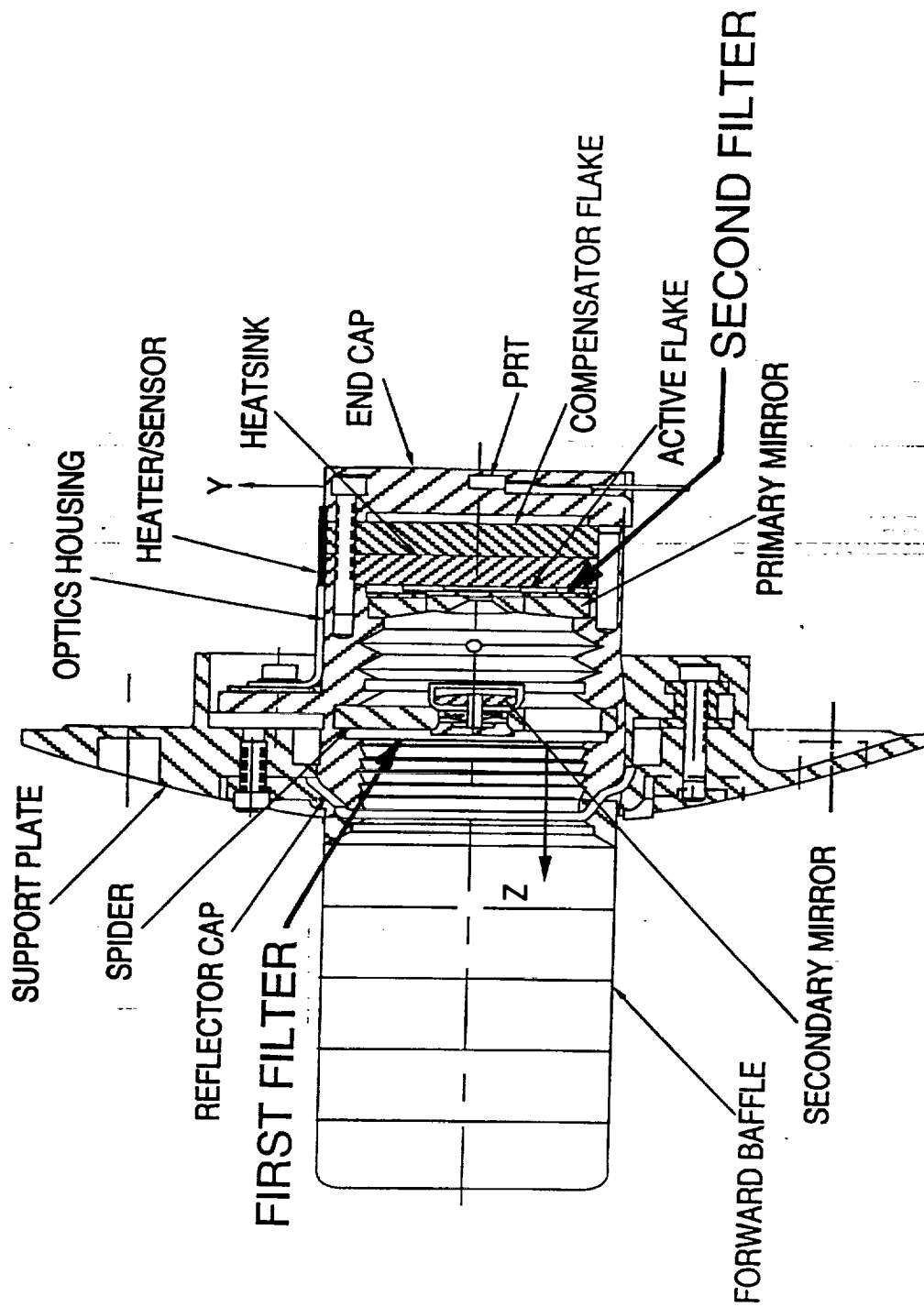


Figure 1.

Data from the CERES/Terra instruments are being validated at present and should be available within a year.

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Figure 3. LDF for clear sky over ocean and land for 18°S to 36°S for 8-12 μ band and for broadband OLR.

Figure 4. LDF for partly cloudy sky over ocean and land, Equator to 18°N for 8-12 μ band and for broadband OLR.

Figure 5. Window channel flux map for 1 January 1998..

Figure 6. Broadband OLR flux map for 1 January 1998.

SPECTRAL RESPONSES

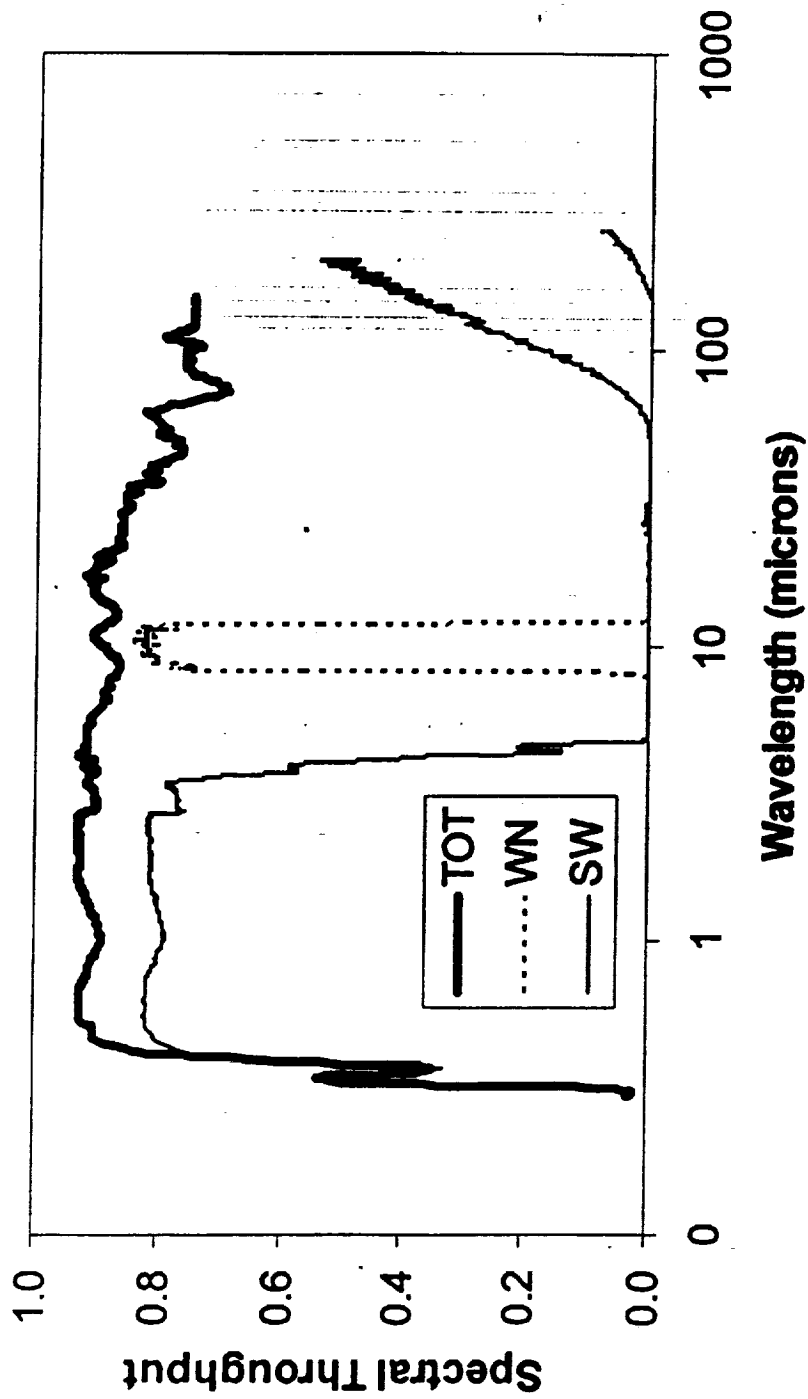


Figure 2.

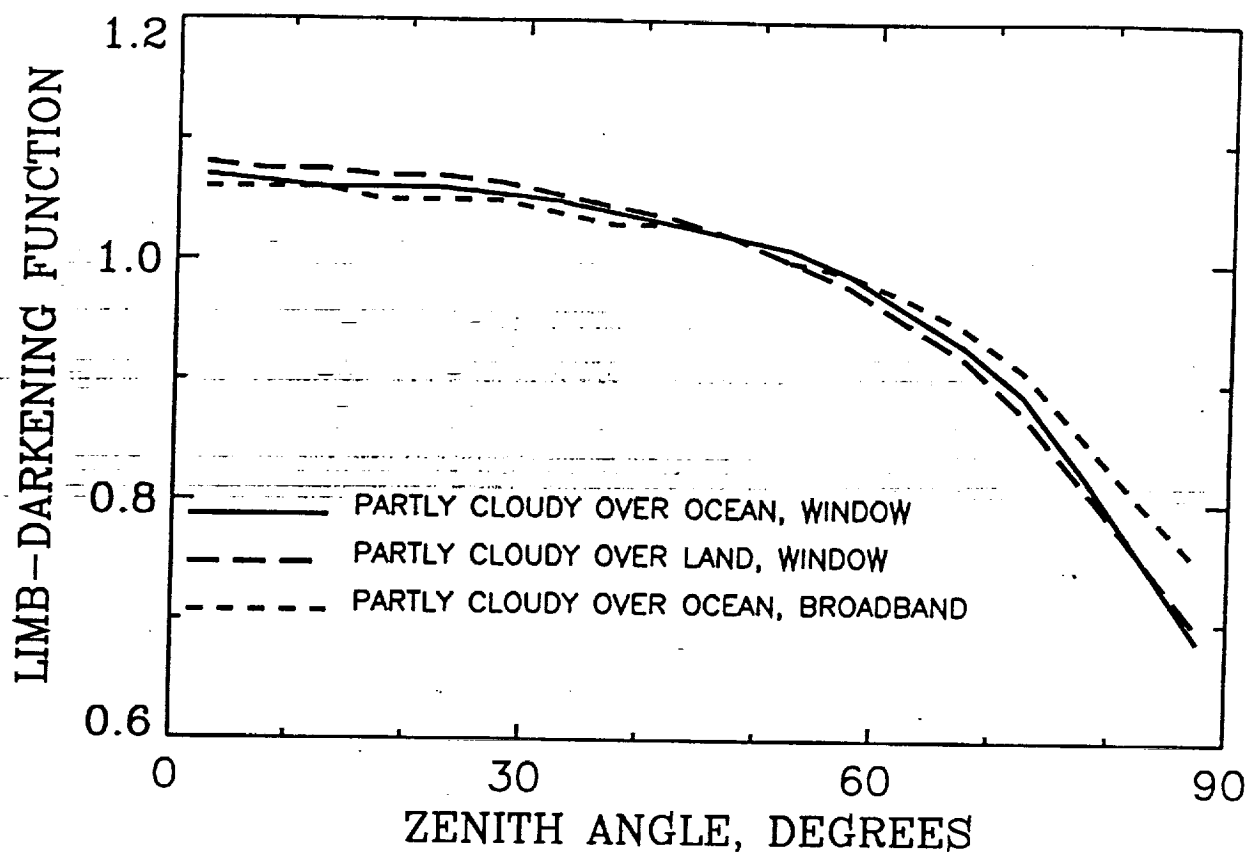


Figure 4

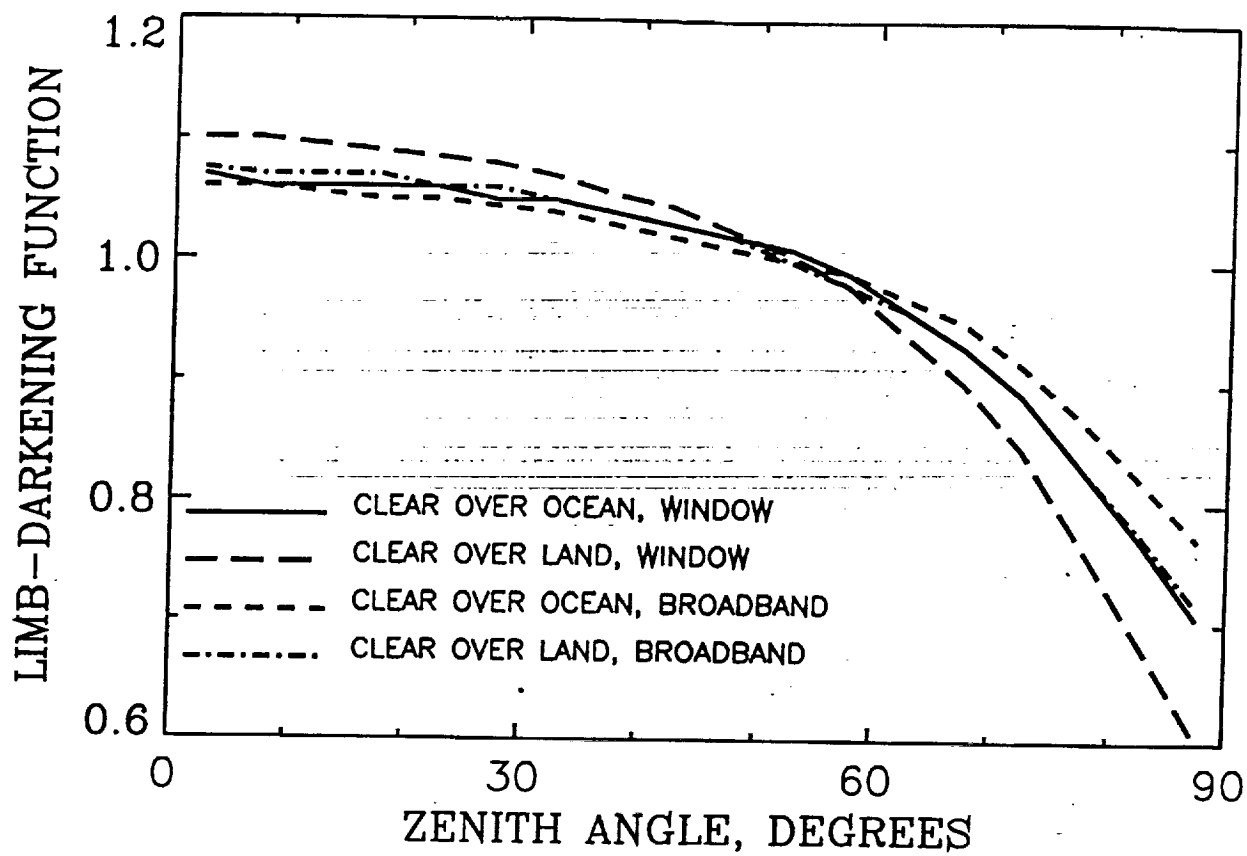
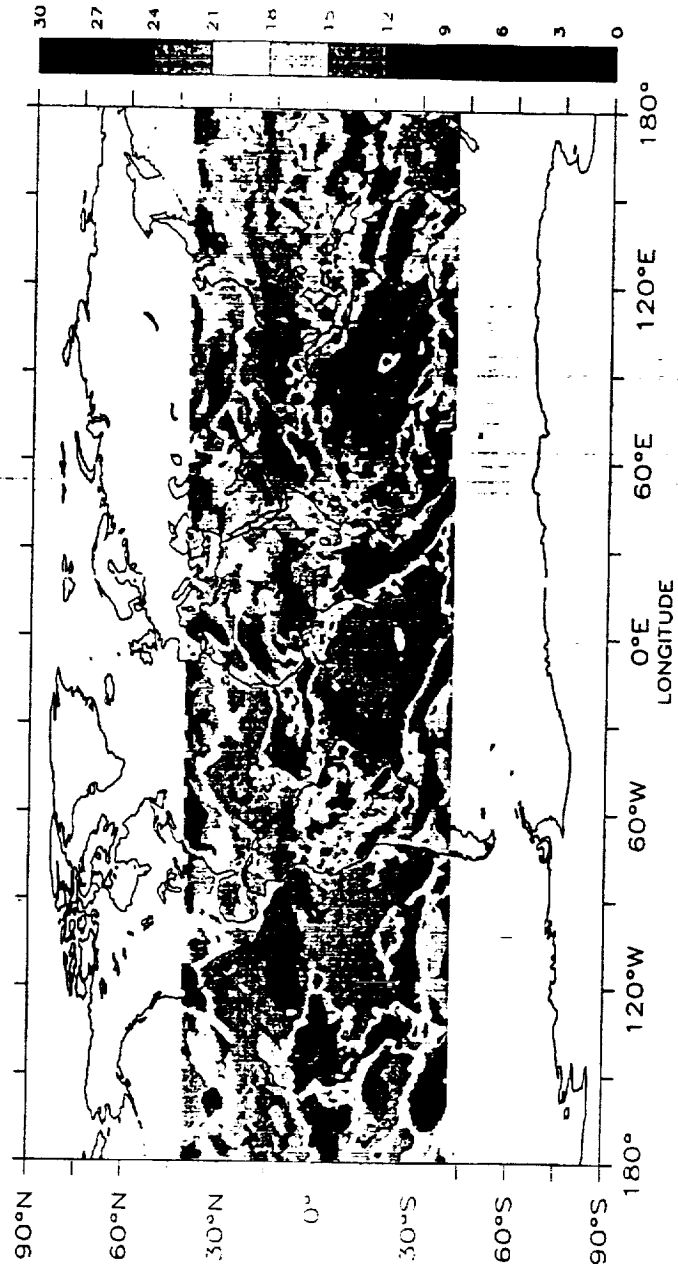
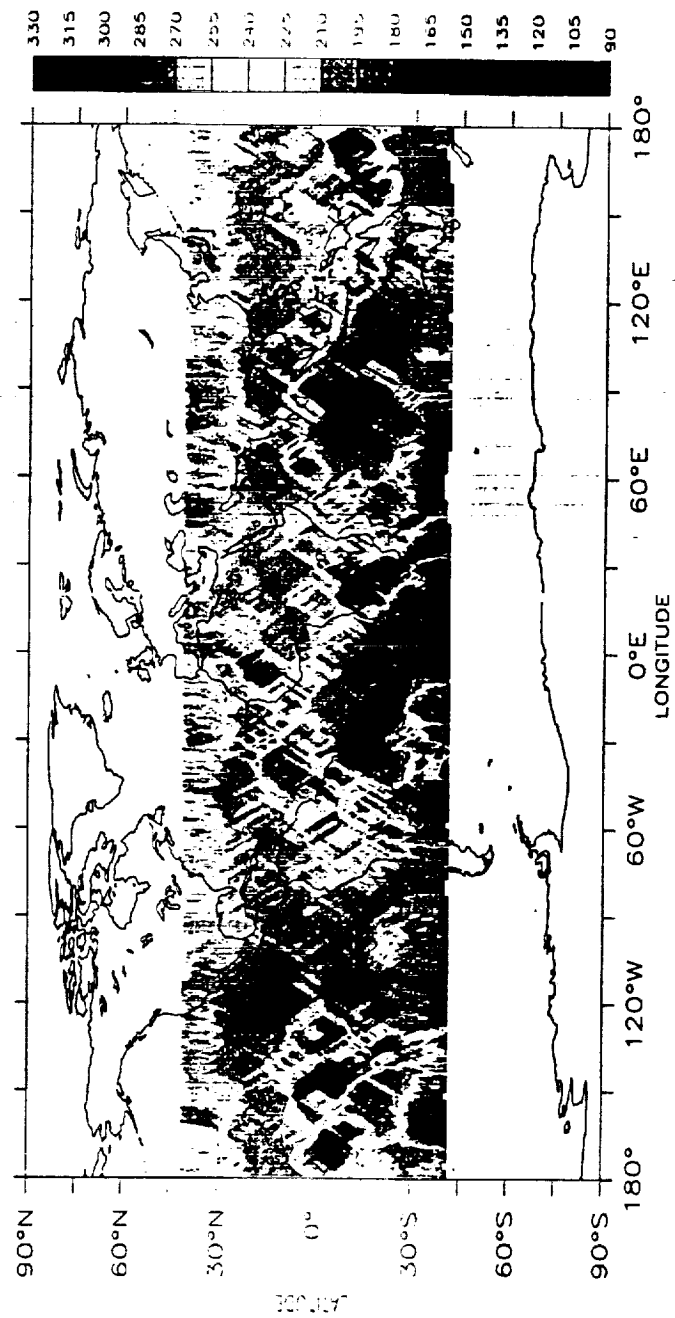


Figure 3

CERES 8-12 Micron Radiance for January 1 1998, W/M²/Micron





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APPENDIX K: NASA Langley Research Center, USA

Studies of Diurnal Processes

M. G. Mlynczak, G. Louis Smith and Bruce A. Wielicki

GERB measurements will be useful for a broad range of radiation budget studies. The present discussion is limited to diurnal processes, for which GERB will provide accurate radiation measurements for the first time. Diurnal processes have been studied using Meteosat and GOES data from narrow band channels (Minnis and Harrison, 1984; Duvel and Kandel, 1985; Cheruy et al., 1991), but deficiencies of extracting broadband radiation components from narrowband channels limit the accuracy with which one can retrieve outgoing longwave radiances and reflected solar radiation. Diurnal variations are strongest in low latitudes, where radiation plays a major role in deserts and in deep convective processes. A better understanding of weather and climate in these regions will be provided by GERB data. Because weather systems are quite mobile, weather in these regions can ultimately affect other regions far away. We discuss some phenomena for which GERB will provide greatly needed data for improved understanding.

The diurnal cycle of outgoing longwave radiation OLR over the Sahara Desert is the strongest over the planet (Harrison et al., 1988) and has been studied by Duvel and Kandel (1985). Charney (19??) explained the flow over a desert in terms of the subsidence due to OLR. This explanation is verified by noting that the deserts stand out in maps of monthly-mean net radiation as having large negative values.

The deep convection regions of the Congo Basin and the Amazon also have very strong diurnal cycles. These are manifested by a pattern of clear mornings, with low clouds developing in the afternoon and developing into deep convection in late afternoon and evening, which clears by morning. The cycle operates as follows. Solar energy is absorbed at the surface and much is converted into latent heat by vaporizing surface water and by evapo-transpiration. By afternoon, sufficient energy is stored at low level that when the sensible heat has developed an unstable temperature profile, the system erupts into a deep convection system in which the latent heat of vaporization lifts air from the boundary layer to near the tropopause. The system is a steam engine which absorbs solar energy, converts it to latent energy and then to potential energy. The lifted air then flows from the deep convective region at high altitude and is replaced by air flowing into the region in the boundary layer. Most of the water in the process is recycled several times before flowing out the Congo or Amazon River. Water which flows out the river is replaced by moisture in the incoming boundary layer flow. The air which has been lifted to high altitude then flows to the subsidence regions of the globe. Thus, the coupled deep convection/subsidence system is a heat engine with solar radiation in the deep convective regions as the heat source and outgoing longwave radiation in the subsidence regions as the heat sink.

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During boreal winter the deep convective regions move northward. The result is that in Africa the deep convection moves toward the Sahel, bringing the wet season. Meso-scale convective complexes MCC occur here frequently (Laing and Fritsch, 1997; Haile et al., 1994). MCC develop as the result of absorption of solar radiation to generate latent and sensible heat to form a set of deep convective cells. When this set of cells is organized by the synoptic scale pattern, the individual storms can coalesce into an MCC, which has a life of its own and lasts for several days. Such systems are not only of regional interest. From June through October, depressions moving with easterlies from West Africa across the Atlantic Ocean are carefully watched, as they can organize the high latent heat over the Caribbean region into tropical storms and hurricanes.

Although not in the part of Earth which is viewed by GERB, the Great Plains of the United States are greatly affected by MCC (Mattox, 1980). MCCs were not discovered until geosynchronous satellite imagery made it possible to observe them. However, they are responsible for most summertime precipitation over the Plains. Furthermore, they develop into synoptic processes which then propagate to affect the eastward part of the US. For this reason, a GERB on a GOES would be extremely valuable for understanding these very important processes over the US.

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